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IUE Atlas of Reconstructed Spectra of Hot Binary Stars

ANNUAL PERFORMANCE REPORT
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1. Project Summary

The *IUE* archive is a very rich source of information on the spectra of all kinds of hot stars and, in particular, hot stars in spectroscopic binary systems. We have begun to apply the Doppler tomography algorithm to reconstruct the individual component UV spectra of stars in a complete sample of hot binaries that have been observed with *IUE.* This sample is based on all the binary systems with primaries of spectral types O, B, A, and F that are listed in the "Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems" (Batten, Fletcher, & MacCarthy 1989, Publ. Dom. Astrophys. Obs., 17). Our primary goals are:

- to produce an atlas of reconstructed spectra (covering wherever possible both the short and long wavelength range observed by *IUE*) which will be published in both paper and digital form,
- to obtain improved estimates of the velocity curve, mass ratio, temperature, gravity, UV intensity ratio, and projected rotational velocity for stars in each system, and
- to make a preliminary survey for abundance anomalies through comparison with standard spectra. The reconstructed spectra of interesting targets will be available to investigators (including ourselves) who wish to conduct a quantitative spectrum synthesis analysis to determine precise abundances.

This census of the spectral properties of the components of some 68 binary systems will provide the basic data to study their evolutionary status. The results will help establish the importance of mass and angular momentum transfer and loss in binary evolution, and will provide a better foundation to understand the final evolutionary paths of massive binaries.

During the first year of support, we have concentrated on refining our methods, and our initial sample is based on binaries of O-type stars. We now have assembled *IUE* high dispersion, SWP spectra on some 46 O-binaries, and we have completed the analysis of six of these systems. Most of this work is included in the Ph.D. dissertation of Dr. Laura R. Penny (who graduated in June 1996). We expect to begin work on the cooler binary systems in the year ahead with the goal of completing the *IUE Atlas of Reconstructed Spectra of Hot Binary Stars* by the end of 1997.

Several related projects have been completed in the first year. Penny (1996) has shown that the cross-correlation functions derived from *IUE* spectra of a target and narrow-lined star (used for orbital velocity measurements) are also important probes of stellar projected rotational velocity and pulsation. Our work suggests that the signature of pulsation is found in many rapidly rotating, O-type stars. Many of the binaries that we will present in the *Atlas* are close systems in which the stellar winds of the individual stars will collide in a bow shock between the stars. We are pursuing a joint UV/optical spectroscopic study to search for evidence of such colliding winds among the O-binaries (the subject of Michelle L. Thaller's dissertation work).

2. Bibliography

- Penny, L. R., Gies, D. R., and Bagnuolo, W. G. 1996, "Ultraviolet Spectral Typing and Luminosity Classification of O-type Stars", *Astrophysical Journal*, **460**, 906-913.

  We present equivalent width measurements of ultraviolet photospheric lines that are useful as spectral type criteria; these include 23 lines of He II, C III, N III, N IV, O IV, Si III, Si IV, S V, Fe IV, and Fe V in *IUE* spectra of 67 O3 to B0 stars of all luminosity classes. Seven lines and two line ratios are particular ly sensitive to spectral type, and we show how the ultraviolet spectral typing diagnostics lead to types that are consistent with optical types. There are few luminosity sensitive photospheric lines in the ultraviolet but we find that the N IV $\lambda1718$ line does have a significant luminosity variation among most O subtypes. This criterion leads to ultraviolet classes that are approximately in agreement with optical luminosity classes. This scheme was developed in order to estimate the spectral types and luminosity classes of tomographically separated component spectra of O-type binary systems.

- Penny, L. R. 1996, "Projected Rotational Velocities of O-type Stars", *Astrophysical Journal*, **463**, 737-746.

  I present an homogeneous set of projected rotational velocities for 177 O-stars based upon *IUE* high dispersion spectra of the UV photospheric lines. The line widths are estimated by cross-correlating each spectrum with the spectrum of a narrow-lined O-star (HD 34078), and the widths of the cross-correlation functions are transformed to projected rotational velocity using a calibration based on the $V \sin i$ data of Conti & Ebbets (1977). The sample includes 120 stars in common with those of Conti & Ebbets plus 57 new targets. I identify 10 stars as potential new double-lined spectroscopic binaries and 20 rapidly rotating stars as possible new line profile variables (displaying bumpy profiles associated with nonradial pulsation). There are few narrow-lined stars among the more massive and more evolved O stars which suggests that macroturbulent broadening is important in such objects. The fastest rotators are found among the lower mass O stars, which may reflect a loss of angular momentum through stellar winds among higher mass stars.

- Fullerton, A. W., Gies, D. R., and Bolton, C. T. 1996, "Absorption Line Profile Variations Among the O Stars. I. The Incidence of Variability", *Astrophysical Journal Supplement Series*, **103**, 475-512.

  We have conducted a spectroscopic survey of a magnitude-limited sample of O stars to search for intrinsic absorption line profile variations, particularly those attributable to nonradial pulsations. Our final sample consists of 30 stars that cover the full range of luminosity classes for spectral types between O4 and O9.7. For these objects, we obtained high resolution, high signal-to-noise ratio spectroscopic time series of the C IV $\lambda\lambda$5801, 5812 doublet and the He I λ5876 triplet. These time series typically consist of 20 spectra per object, and sample time scales ranging from a few hours to $\sim$1 week. We developed a new technique, Temporal Variance Spectrum analysis, to detect line profile variations in these data in an objective, statistically rigorous manner.

  As the primary result of this survey, we report the detection of statistically significant line profile variations in at least one of the absorption lines for 77% (23/30) of our sample. The incidence and amplitude of variability increase with increasing stellar radius and luminosity, so that all the supergiants in our sample exhibit line profile variations and, conversely, the non-variable stars are mostly dwarfs. We found no statistically significant line profile variability for dwarfs earlier than O7.

  The observed distribution of line-profile variables in the HR diagram agrees approximately with the predicted domain of strange-mode oscillations, even though many of the variations in the spectra of supergiants must, in the first instance, arise in the stellar wind. We discuss ways of reconciling these two, apparently contradictory, aspects of the observed activity in terms of mechanisms that causally link variations in the stellar photosphere to the formation of structure in the stellar wind, especially the strong line-driven instability. Although the true nature of the widespread line-profile variability remains an open issue, it seems likely that pulsation is responsible for much of the observed activity.

- Stickland, D. J., Lloyd, C., Penny, L. R., Gies, D. R., and Bagnuolo, W. G., Jr. 1996, "Spectroscopic Binary Orbits from Ultraviolet Radial Velocities. Paper 21: HD 152248", *The Observatory*, in press (no abstract).

- Gies, D. R., Barry, D. J., Bagnuolo, W. G., Jr., Sowers, J., and Thaller, M. L. 1996, "Spectroscopy of the Massive Binary Iota Orionis at Periastron", *Astrophysical Journal*, **469** (October 1, 1996 issue), in press.

  Iota Orionis is a massive binary with a very eccentric orbit which brings the stars into close proximity at periastron. The resulting tidal deformation of the primary star is expected to create enhanced mass loss and stimulate stellar oscillations at each periastron. We present the results of a search for these effects in high S/N spectra of the Hα and He I λ6678 profiles of ι Ori obtained over 5.5 hours during a single periastron passage. We fit the He I λ6678 data using previously determined profiles for both components and using the orbital solution of Stickland et al. (1987) to establish that periastron occurred at HJD 2,450,072.80$\pm$0.03. Measurements of the projected rotational velocities indicate that both stars rotate more slowly than the orbit at periastron. There is weak, residual Hα emission that moves with the primary's orbital motion and that may be associated with the development of an enhanced, focused wind at periastron. However, the He I λ6678 line of the primary star is nearly constant in shape over this interval, and we find no evidence for tidally induced oscillations.

- Gies, D. R. 1996, "O and B-star surface mapping", in *IAU Symposium 176: Stellar Surface Structure*, ed. K. G. Strassmeier & J. L. Linsky (Dordrecht: Kluwer Academic Publishers), 121-128.

  The profile variations observed in the spectra of OB stars provide strong circumstantial evidence that their photospheres are modulated by the effects of nonradial pulsations. Future high S/N observations that record *lpv* in a variety of lines (with differing temperature sensitivities) offer the promise of determining the spatial distribution of the NRP modes and the actual stellar rotation speeds (especially in very rapid rotators like ζ Oph). Such observations will give us a first glimpse of what the surfaces of hot stars will look like when observed directly through long baseline interferometry. In addition, such observations will provide new understanding about the role of NRP for episodic mass loss in hot stars and will expand the field of asteroseismology into the hot star regime.

- Gies, D. R. 1996, "Observations of Colliding Winds in O-type Binaries", in *Workshop on Colliding Wind Binaries*, ed. V. Niemela & N. Morrell, Revista Mexicana de Astronomía y Astrofísica - Serie de Conferencias, in press

  Stellar winds will collide in a bow shock in close binary systems of O-type stars. The presence of this boundary will truncate the full spatial extent of the two individual winds, and thus the spectral lines formed in the wind will appear differently when viewed from different orientations. Here I discuss the orbital variations of the UV wind lines in a large sample of O-binaries that have been observed with the *International Ultraviolet Explorer Satellite (IUE)*. High density regions in the wind (near the photospheres and bow shock) will produce optical emission lines, and I describe the Hα emission properties of several systems. The physical characteristics of the component stars can now be better estimated through Doppler tomography, a numerical method to extract the individual primary and secondary spectra.

- Thaller, M. L. 1996, "Detection of Colliding Winds in O-Type Binaries", in *Workshop on Colliding Wind Binaries*, ed. V. Niemela & N. Morrell, Revista Mexicana de Astronomía y Astrofísica - Serie de Conferencias, in press

  The evolutionary paths of massive close binary stars depend in large measure on the relative importance of mass loss and mass transfer, and although mass loss in single massive stars is relatively well understood, the situation for binary stars is much more complex. If both stars have significant winds, the winds will collide and form a bow shock between the stars. We have begun a series of investigations on the orbital phase variations in Hα and the UV wind lines of O-type binaries to better understand the geometry of the wind-wind interaction. While the UV wind lines sample the large scale wind structure, the Hα emission is formed by recombination in regions of relatively high density, and thus it helps probe conditions in the base of the wind and in other regions of enhanced density (such as the bow shock). We present here the preliminary results from our survey of the Hα and He I λ6678 lines.

- Penny, L. R. 1996, "Doppler Tomographic Separation of UV Spectra in O-Type Binary Systems", *Bulletin of the American Astronomical Society*, **187**, #60.05.

  Knowledge about the individual components of O-type binaries is difficult to obtain because of the severe line blending present in their spectra. An important new method is Doppler tomography, an iterative scheme that uses a set of orbital phase distributed spectra and both radial velocity curves to reconstruct the individual component spectra (see Bagnuolo, Gies & Wiggs 1992, ApJ, 385, 708). These individual spectra can then be analyzed to determine various physical properties of the stars. The spectral types and luminosity classes obtained provide indicators of the temperatures and gravities. The individual projected rotational velocities can be used to test for rotational synchronization of the orbit or rapid spin-up due to mass transfer. An estimate of the magnitude difference together with the combined absolute magnitude results in individual luminosity estimates. Finally, it is possible to search for abundance differences due to mass transfer or loss.

Here I present the first results of a program of Doppler tomography of O-binaries observed with the IUE. The use of IUE high dispersion spectra is optimal for O-type binaries because of the presence of many photospheric lines in the UV (high excitation lines which are relatively free from contamination from circumstellar emission often found in their optical spectra). I describe cross-correlation methods that use narrow-lined spectral templates to obtain precise radial velocities and orbital velocity curves which are used in the tomography algorithm. I also show how these cross-correlation results can be used to estimate projected rotational velocities and UV magnitude differences. I have identified new spectral classification criteria based on UV photospheric lines that are directly applicable to these O-binaries. I present results for three systems: DH Cep, HD 165052, and HD 93403. All are double-lined spectroscopic binaries with periods ranging from 2.1 to 15.1 days. These systems are used as tests of current theories for massive close binary evolution.

- Penny, L. R. 1996, "Doppler Tomographic Separation of UV Spectra of O-Type Binary Systems", Ph.D. dissertation, Georgia State University.

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Here I present the first results of a program of Doppler tomography of O-binaries observed with the *International Ultraviolet Explorer Satellite (IUE)*. The use of *IUE* high dispersion spectra is optimal for O-type binaries because of the presence of many photospheric lines in the UV (high excitation lines which are relatively free from contamination from circumstellar emission often found in their optical spectra). I describe cross-correlation methods that use narrow-lined spectral templates to obtain precise radial velocities and orbital velocity curves which are used in the tomography algorithm. I also show how these cross-correlation results can be used to estimate projected rotational velocities and UV magnitude differences. I have identified new spectral classification criteria based on UV photospheric lines that are directly applicable to these O-binaries. I present results for six systems: HD 215835 (DH Cep), HD 165052, HD 93403, HD 93205, HD 149404, and HD 152248. All are double-lined spectroscopic binaries with periods ranging from 2.1 to 15.1 days. These systems are used as tests of current theories for massive close binary evolution.